Canada Centre for
Mineral and Energy Technology

Centre Canadien de la technologie
des minéraux et de l'énergie

CANMET

Canada Centre for Mineral and Energy Technology

Centre canadien de la technologie des minéraux et de l'énergie

102-06539/

Observation of the Shock Resistance of Emulsion Explosives in Rock Blasting

Q. Liu, J.P. Tidman, D. Tunaley and J.J. Mullay

MRL 94-063 (OPJ) December 1994

To be presented at the International Society of Explosives Engineers'

11th Symposium on Explosives and Blasting Research

February 5 - 9, 1995

Nashville, Tennessee, U.S.A.

and for

Publication in the Proceedings of the Symposium

Observation of the Shock Resistance of Emulsion Explosives in Rock Blasting

Qian Liu, CANMET/MRL Experimental Mine
P.O. Box 1300, Val d'Or, Québec, Canada J9P 4P8

Paul Tidman, ICI Explosives Group Technical Centre
McMasterville, Québec, Canada J3G 1T9

Deane Tunaley, ICI Australia Operations Pty Ltd
P.O. Box 196, Kurri Kurri, NSW 2327, Australia

John Mullay, ICI Explosives USA Inc.
P.O. Box 577, Tamaqua, PA, 18252 0577, USA.

Abstract:

Laboratory studies have indicated that the crystallization and desensitization of microballoon sensitized emulsion explosives start immediately after shocking or pre-compression. However, the question of whether or not the shocked emulsion could be worsened by the growth of crystallization or recovered by rebounding back to lower densities has been rarely examined under actual rock blasting conditions. This study was primarily intended to investigate the desensitization characteristics of two commonly used emulsion products in terms of blasthole spacing and delay duration. In the experiment, two parallel blastholes, 32 mm in diameter and 1.7 m deep, were drilled downwards in an underground drift. Full coupling was achieved by tamping the explosives in the wet holes. The donor hole was always loaded with the same

explosive while changing the explosive in the receptor hole. The receptor hole is initiated with a delay following the donor hole in order to observe the timing effect on the explosives being shocked. High frequency vibration monitoring was used to identify the detonation or failure of the receptor hole. The spacing was varied to modify the shock pressure the receptor charges are subjected to. Dynamic pressures in the receptor hole were also measured at different distances from the donor hole. The shock resistance was measured by the minimum spacing without desensitization. In general, the Superfrac™ exhibited better shock resistance than Magnafrac™. The shock resistance of both emulsions was not affected by delay times. The delay-independence of tested emulsions indicates that the crystallization of emulsion may happen immediately after the shocking, however, the shocked emulsion is not worsened, nor recovered. The observation results also give the typical spacing values for field consideration to avoid the problems of explosives malfunction with the use of either long or short delay detonators.

Figures follow the text.

1. Introduction

An important property of cap-sensitive, small diameter products is the ability to function effectively despite being shocked by nearby blastholes. A systematic study of this feature was carried out in lab tests [1] in which a standard donor explosive was used to shock test cartridges through a water medium. The results contained contradictory evidence concerning the effect of emulsion crystallization on pressure desensitization. One serie of experiments suggested that the loss of sensitivity was mainly due to the destruction of hot-spots (e.g. glass microballoons). Another series indicated that the emulsion breakdown played the most important role in loss of sensitivity.

It was recognized that the laboratory results may not be fully representative of an emulsion's performance in actual rock blasting. A further step was to undertake the pre-compression testing in a real mining environment. A hard rock site was chosen as it was thought to provide the most consistent shock transmission conditions. The goals of the tests were to provide data to identify the desensitization process and to establish the desensitization limits under real mining conditions.

2. The Performance of Explosives under Pre-compression in Rock Blasting

Once an explosive charge is loaded into a blasthole, its performance is subjected to the in situ surrounding conditions such as rock strength, fracture joints, borehole deviation, spacing

and delays, etc.. Among these factors, spacing and delay are the controllable parameters which are commonly used in a blast design and can be properly chosen to achieve the desired performance of an explosive. Therefore, the general phenomenon of explosives malfunction, including sympathetic detonation, desensitization and cut-offs, can be illustrated on a spacing-delay chart, as shown in Figure 1 [2].

The spacing-delay chart is divided into five regions to represent different phenomena: (I) undisturbed rock, (II) sympathetic detonation, (III) desensitization, (IV) normal detonation and (V) cut-offs. The boundary of the undisturbed rock (Zone I) with others is the shock wave (strong stress wave) propagation radially outwards from the donor hole. The slope of the boundary represents the shock velocity which is higher than (but close) to the velocity of sound in the rock. When the receptor hole is located very close to the donor hole, sympathetic detonation (Zone II) will happen, regardless the delay time.

With further spacing, in Zone III, explosives could be desensitized by pre-compression. In Figure 1, two types of explosives are given as examples. Water-gel A is considered to have a larger spacing range of desensitization than Emulsion A. However, the sensitivity can be recovered after a waiting period as exhibited by water-gel or slurry type of explosives. Unlike water-gels, emulsions sensitized with microballoons may have higher shock resistance but usually have very little or no recovery capability. The desensitization in this case is caused by permanent damages to the microballoons and the water-in-oil matrix. In the case of gas sensitized emulsions, the sensitivity may also be recovered with a certain waiting period depending on the quantity of gassing agent added in.

Beyond the desensitization region is the normal detonation (Zone IV), which means that

the shocked explosive is still detonatable although the VOD might be modified to a certain degree. Blast design should attempt to keep spacing and delay outside the desensitization region. The Cut-off region (V) means that the collar charges in the receptor hole are lost by rock movement or by gas ejections through cracks from the donor hole. The Cut-off region normally intersects with the desensitization region (III) and the normal detonation region (IV). More damage to the receptor hole occurs the closer the spacing and, therefore, the more cut-offs of explosives. Typically, 60 cm of charges in the receptor hole could be cut off by the crater of the donor hole (32 mm diameter) if the spacing is about 30 cm apart in development rounds. Furthermore, if the spacing is large enough, the receptor hole could not be affected by the detonation of the donor hole. In this case, the horizontal line on the top of Zone V represents the upper limit of spacing with cut-offs.

Considering the above phenomena, the pre-compression experiment for emulsion explosives was designed to determine the critical spacing and delay values between desensitization (Zone III) and normal detonation (Zone IV). The pre-compression experiments were conducted on the 70 m Level at the CANMET/MRL Val d'Or Experimental Mine.

3. Pre-compression Experiment in Hard Rocks

3.1. Rock and Explosives Properties

The CANMET/MRL Experimental Mine is located about 500 km north-west of Montreal, in a formerly operating gold mine. The geology in this mine is composed of mainly virgin,

unfragmented granodiorite with some narrow quartz veins and shear zones. The pre-compression experiments were conducted at the 70 m level on the side walls of a drift in the granodiorite host rock. The rock elastic properties are summarized in Table 1.

The properties of the two emulsion products are summarized in Table 2. The Superfrac 4000 was used as the standard donor charge while the receptor hole is loaded with either Superfrac 4000 or Magnafrac 1000. Both emulsions are non-aluminized products. Magnafrac 1000 is a straight emulsion sensitized by microballoons. The Superfrac contains ammonium nitrate prills in the emulsion.

Table 1. Rock Elastic Properties

Density	2.71 g/cm^3	Young's Modulus	59.1 GPa
P-Wave Velocity	5478 m/s	Poisson's Ratio	0.31
S-Wave Velocity	2888 m/s		

Table 2. Specifications of Explosives

Parameters	Superfrac 4000	Magnafrac 1000
Cartridge size:	25mm x 300mm	25mm x 300mm
Density:	1.18 g/cm^3	1.12 g/cm^3
Confined VOD:	4300 m/s (32 mm dia.)	5200 m/s (50 mm dia.)
Weight strength (ANFO=100)	89	80

3.2. Experiment Methodology

Figure 2 illustrates the set-up of the experiment and monitoring system. There are two intersecting drifts at the experimental site. The experimental drift is about 50 m long with a dimension about 2.1 m × 2.4 m. Blastholes are drilled on the side walls of this drift. In the instrumentation drift, a portable laboratory was installed for recording and control equipment. It also served as a refuge station while waiting for fumes to be ventilated out. For each experiment, two parallel blastholes, 32mm (1.25") diameter, were drilled 1.7 m (6 ft) deep on the side wall with a downward angle (10° - 15°). The holes were inclined to keep water inside for better coupling between the tamped explosives and the borehole wall. The spacings between the two holes are varied from 140 mm to 350 mm in order to adjust the pressure to which the receptor charge is subjected. The donor hole was initiated by a "zero" delay detonator and the receptor hole by a delay detonator, 25 ms - 500 ms, except the separately fired shots with 20 minute waiting periods.

Vibration monitoring was used as a major tool to observe the behaviour of the receptor hole. Two sets of high frequency geophones were installed, one set on each side of the experimental drift. Each set had three geophones for triaxial measurement. Figure 3 shows two typical recordings for Superfrac 4000 with the same 100 ms delay. The upper trace shows a desensitization with 190 mm spacing while the lower trace is the case of normal detonation with 200 mm spacing. In general, if the receptor is desensitized, there would be no vibration for the delay time used. Only one vibration peak is shown on the recording. If the receptor hole undergoes a normal detonation, two vibration peaks should show up on the recorded trace. In

most cases, the magnitude of the vibration, e.g. the peak particle velocity, of the receptor hole is smaller than the donor hole because of the loss of charges at the collar part.

VOD measurement was made for some donor holes but not for the receptor holes because of the cut-off problem around the collar of the receptor hole produced by donor hole cratering. The measured VOD for the Superfrac 4000 ranges from 4410 m/s to 4597 m/s, with an average of 4527 m/s. A high speed video system was also employed in this study to visually observe the face movement around the blast. It was found that the rock fragments around the receptor hole are moved 300 mm in less than 20 ms after the donor hole is initiated. This explains why VOD measurement of the receptor hole could not be successful.

Visual judgement of desensitization or normal detonation is possible by examining to the appearance of the borehole wall. A normal detonation can create a rough and fractured borehole wall while a desensitized charge does not change the smoothness of the borehole wall.

A quick *Paper Towel Testing Method* can also be used to determine whether or not an emulsion charge is crystallized. In the case when undetonated charges are blown out to a muck-pile, perhaps even before the detonator fires, pieces of emulsion can be collected and placed on a paper towel. Of course, the emulsion sample has to be "fresh" from the inside of a collected emulsion and free of external water. The paper towel becomes wet very quickly for a desensitized emulsion because the water-in-oil matrix is damaged. By contrast, an undamaged emulsion will not wet the paper towel at all.

4. Experiment Results and Discussion

Figure 4 summarizes the experiment results on a spacing-delay chart for Superfrac 4000. The spacing range tested was between 140 mm (5.5") and 245 mm (11.5") and the delay varied from 25 ms up to 20 minutes, which was designed to observe the effect of crystallization of a damaged emulsion. With the minimum spacing tested, sympathetic detonation was not observed. Desensitization had been found below 190 mm (7.5") spacing while normal detonation was found with spacings above 200 mm (8"). The delay time was found to have no apparent effect on the desensitization of the emulsion explosive, even with 20 minutes waiting time. The long time interval over which shock desensitization is constant permits us to conclude that the desensitization is not due to a temporary constriction of the charge to less than its critical diameter. We also know that crystallization releases heat in a matter of seconds in laboratory shear tests. If the mechanism causing a loss of sensitivity is the same over the entire range of testing interval, then it is not the onset of crystallization.

Figure 5 shows the experiment summary for Magnafrac 1000. The critical spacing is about 250 mm between desensitization and normal detonation. Compared with Superfrac 4000, this spacing is about 50 mm (2") larger, indicating a lower shock resistance. However, the effect of delay time is the same as Superfrac 4000. This result is different from what has been observed before by Mullay, et al. [3]. In that study, the effect of delay timing seemed to have reduced the performance of an emulsion explosive with delay time ranging from 25 ms to 150 ms and borehole spacings of 12" (305 mm) and 18" (457 mm).

The observed difference between the shock resistance of Superfrac 4000 and Magnafrac

1000 is significant. The difference in composition between the two emulsion products is the presence of solid ammonium nitrate in Superfrac. One can postulate that the microballoons are somehow shielded by the solids and survive the shock. However laboratory measurements of the density of pre-shocked cartridges suggest that there is no difference between the amount of surviving microballoons in the two products. Microballoon breakage and some "other" process contribute to the failure of shocked emulsions. For Superfrac, the improved shock resistance may also be due to the hot-spots provided by the ammonium nitrate prills in the forms of phase discontinuity and hollow particles.

The detonators did not appear to have any influence on the outcome of these tests. The delay times of detonators in surviving emulsions were within normal scatter ranges. Magnafrac survived down to a separation distance of 250 mm. Under normal circumstances Magnafrac and Superfrac have about the same sensitivity to initiation. If the initiation ability of the detonator base charge was to be affected by the shock pressures, one would expect that a closer spacing, e.g. the 200 mm spacing limit of Superfrac, would reduce the initiation ability even more. That was not the case. Also, as indicated in the following section, the pressures measured in the shocked cartridges were quite low. Our experience with the initiation output of solid explosives suggests that the observed pressures are not enough to pre-compress the base charge to cause loss of initiation ability.

5. Dynamic Pressure Measurement

The pressure measurements were conducted one year after the initial pressure

desensitization experiments. The location was the 130 m level of the Experimental Mine, in host rock which is the same as the 70 m level. Holes were drilled as previously, dipping slightly downwards into the wall of the drift. Each experiment consisted of a central donor hole and two experimental holes on opposite sides. The spacings (17.5 cm, 22.5 cm and 27.5 cm. or 7 in., 9 in. and 11 in.) were chosen to represent areas where the products were known to pass or fail from the first experimental series. The pairing of spacings were randomized among the 15 donor holes .

The donor holes were charged with the same emulsion donor as used in the first test series. Eight cartridges of 25mm x 300 mm product were slit and tamped into the 1.7 m hole, leaving a 10 to 20 cm collar. The performance of the donor holes was monitored using VOD probes and two vibration stations. The measured VODs were consistent, giving an average of 4350 m/s.

The shock pressure was measured in two types of acceptor holes, one filled with water and one filled with emulsion. The water-filled receptor holes ensured complete coupling between the pressure gauges and the rock. The emulsion-coupled holes give a measure of reality but are also subject to the irregularities of loading and product homogeneity. Again assignment of water and emulsion coupling in acceptor holes was randomized.

The pressure gauge device used for these experiments were carbon resistors. It is well-known that carbon composition resistors exhibit a linear change in resistance with pressure [4]. A batch of Allen-Bradley 470 ohm 1/8 watt resistors have been calibrated against known static and dynamic pressures and a pressure sensitivity of 11.3 bar/ohm measured [5]. In a half-bridge circuit, the change in resistance of the gauge resistor can be derived from the recorded voltage

signal, knowing the supply voltage and the value of the ballast resistor. Using nominal values for these, the circuit gives a sensitivity of 1.5 bar/millivolt. Signals were recorded and stored on a digital oscilloscope. The oscilloscope was triggered by the VOD probe so it is possible to determine the pressure pulse times in relation to the time of the donor charge initiation.

Figure 6 shows the recorded signals for shot P10, which had emulsion- and water-coupled acceptor holes at 23 cm from the donor. These traces are typical of the recorded data and have rather complex features. Note that the rise-times and peak pressures in the emulsion are much less than in water. One unambiguous feature is the first peak of the pressure pulse. In the water-coupled traces, following the initial rise, there are rather violent swings in pressure as the shock wave reflects from one side of the blasthole to the other. These oscillations appear to last as long as 400 microseconds, at which time the pressure drops and the traces become more erratic.

The first peak pressures have been converted from voltage to pressure and plotted in Figure 7. While there is some scatter in the data, there is a definite attenuation of pressure at greater distances from the donor charge. The difference between water- and emulsion-coupled acceptor holes is also clearly shown. A shock wave travelling from one medium to another may only transmit part of the incident energy [6]. The amount of energy transmitted is determined by the acoustic impedance of the two media. The acoustic impedance is defined as the product of density and sound velocity. For the data for the host rock and water, the energy transmitted is 0.3 of the incident energy. Little attenuation is expected when waves travel through water from the acceptor walls to the pressure gauge so a peak pressure of 100 bars in water is equivalent to about 330 bars in the rock.

The pressure peaks in the emulsion-filled acceptor holes are about five times lower than the water-filled holes. This could be due to lower transmitted energy and/or attenuation of pulses through the emulsion. The emulsion's impedance is higher than water and so the transmitted energy should be higher in the emulsion acceptors. The emulsion used in the acceptor holes contains microballoons which attenuate shock waves very quickly.

6. Conclusions.

The superior shock resistance of Superfrac 4000 is demonstrated by the smaller critical blasthole spacing compared with that of Magnafrac 1000. In the situations where blastholes are positioned close to each other, the Superfrac is expected to have better performance due to the higher shock resistance as defined by the critical desensitization spacing. The shock pressures in holes 200 to 300 mm from 32 mm blastholes were enough to cause emulsion crystallization and damage to microballoon hot spots. In spite of this, the explosives detonated at spacings down to the critical desensitization value.

Acknowledgements.

The managements of ICI Explosives and CANMET/MRL are appreciated for their permission to publish this paper. The authors would like to recognize the help of Mr. Richard Cormier of CANMET/MRL Experimental Mine for providing drilling and blast services and of Mr. Alan Hackett of ICI Explosives for the shock gauge measurements.

References.

1. Tunaley, D. "Improving the Precompression Resistance of Emulsion Explosives", Internal Report GTC-B-93/10-17,, ICI Group Technical Centre, 1993.
2. Liu, Q. "The Concept of Explosives Malfunction in Rock Blasting", Proc. of 10th Symposium on Explosives and Blasting Research, pp.51-62, Jan.30 - Feb.3, 1994, Austin, Texas, U.S.A.
3. Mullay, J.J. et al. "Small Scale In-Rock Precompression Testing: Effect of Delay Timing", Proc. of 10th Symposium on Explosives and Blasting Research, pp.75-89, Jan.30 - Feb.3, 1994, Austin, Texas, U.S.A.

4 R.W. Watson, "Gauge for Determining Shock Pressures", Rev.Sci.Instruments **38**, 978, (1967)

5 A. Hackett, "A Dynamic Pressure Calibrator for Overpressure Sensors", ICI Report NR1023, 1993.

6 H. Kolsky, "Stress Waves in Solids", Oxford Press, 1953.

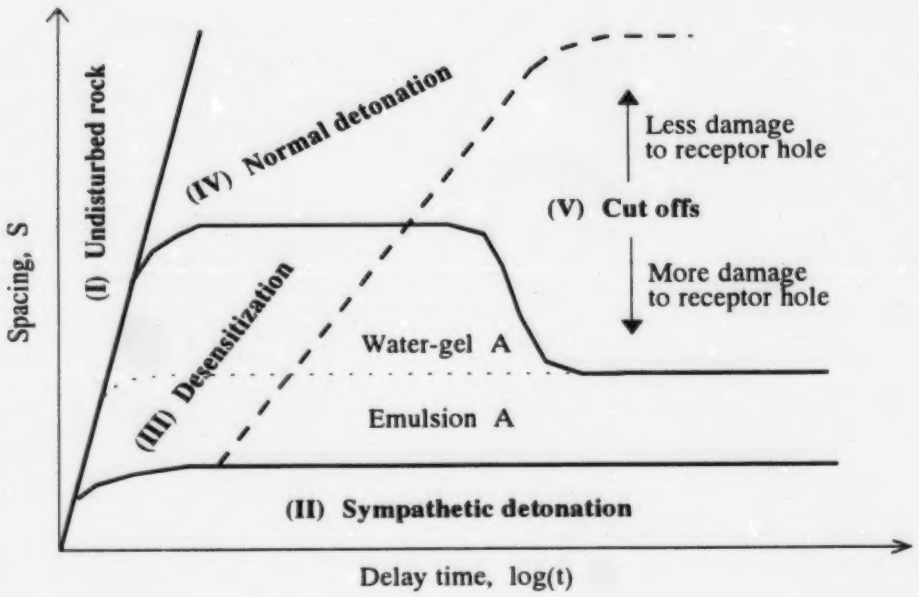

Figure 1. The performance of explosives under pre-compression in rock blasting

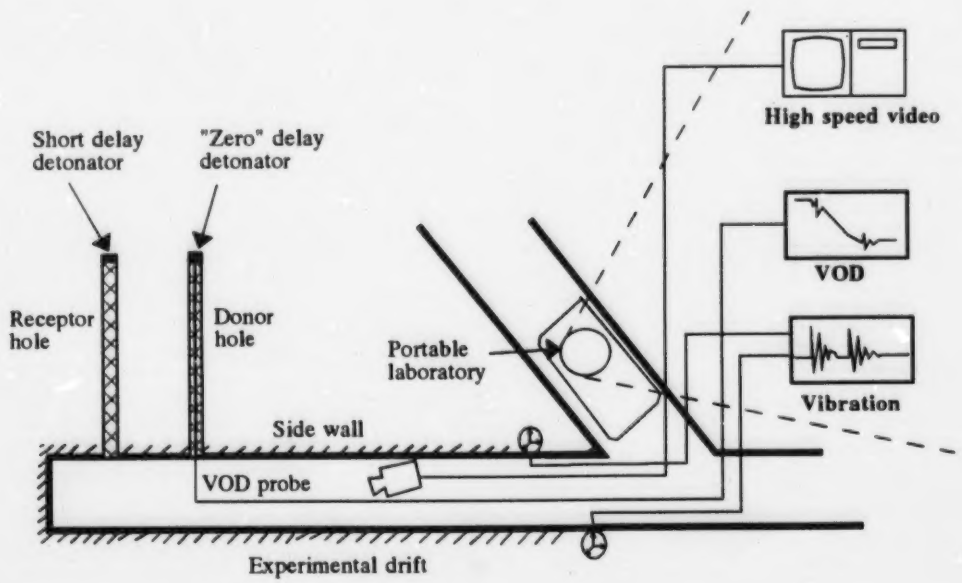

Figure 2. Experiment set-up

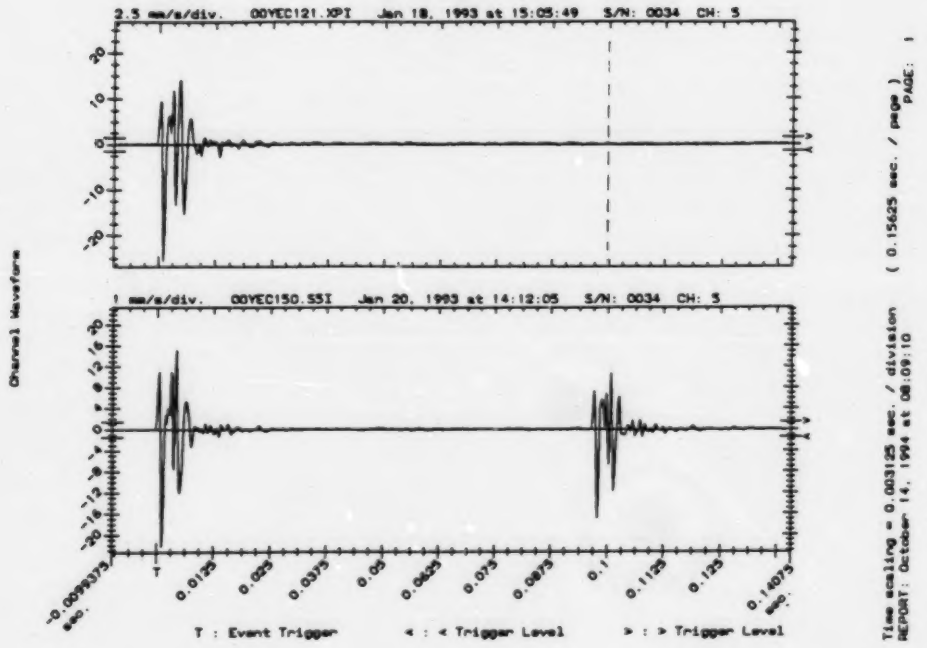
2.5 mm/s/div. 00YEC121.XPI Jan 18, 1993 at 15:05:49 S/N: 0034 CH: 5
1 mm/s/div. 00YEC150.SSI Jan 20, 1993 at 14:12:05 S/N: 0034 CH: 5
Channel Waveform
T : Event Trigger
< : < Trigger Level
> : > Trigger Level
Time scaling = 0.003125 sec. / division
REPORT: October 14, 1994 at 08:09:10

Figure 3. Comparison of vibration recordings for the desensitization (upper trace) and normal detonation (lower trace) for Superfrac 4000

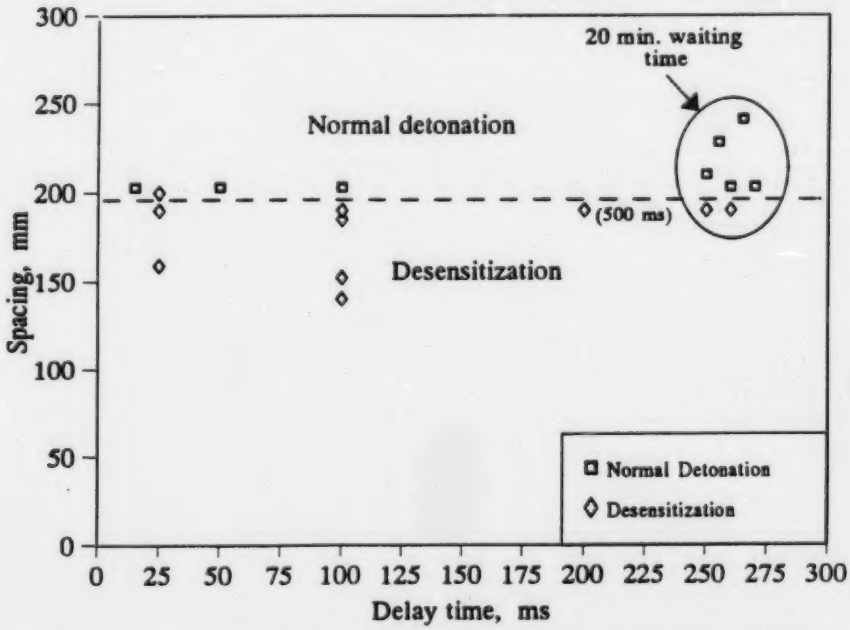

Figure 4. Experiment Summary for Superfrac 4000

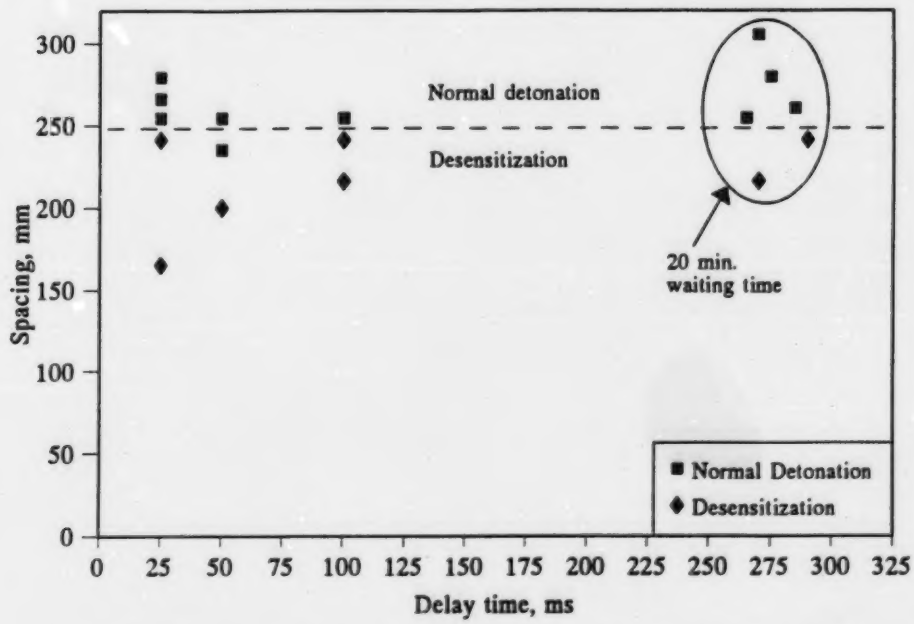

Figure 5. Experiment Summary for Magnafrac 1000

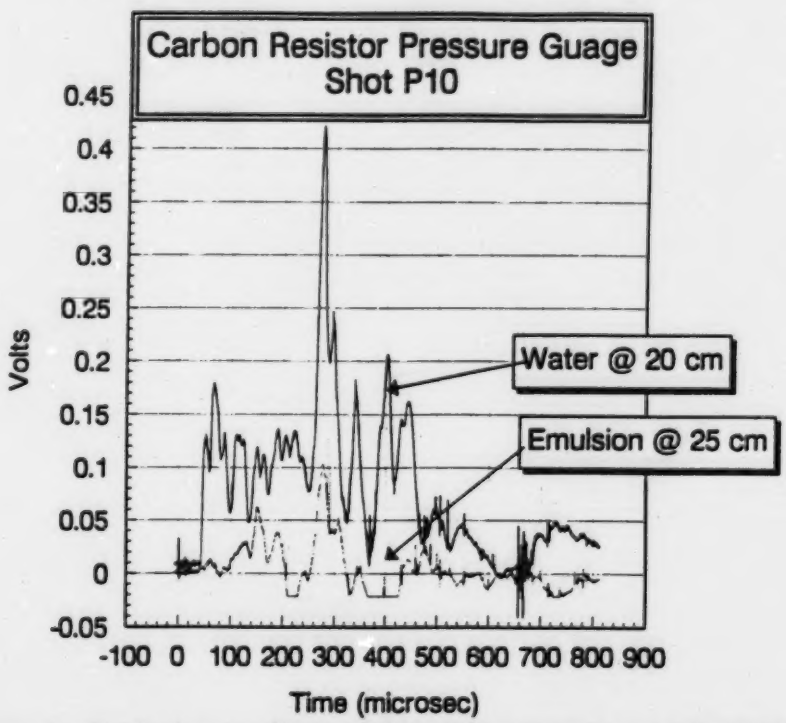

Figure 6. Typical recordings of dynamic pressure measurement

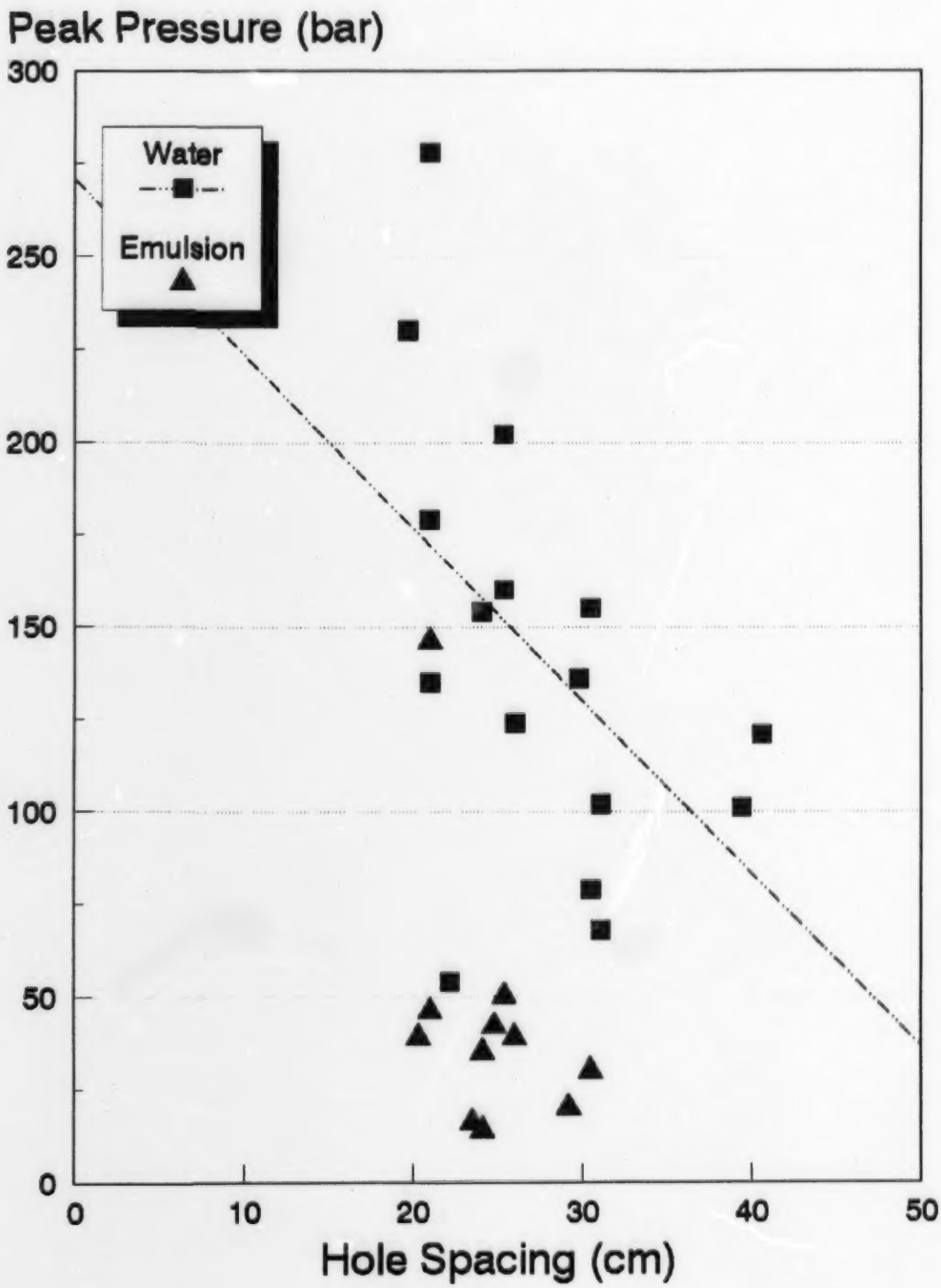

Figure 7. Attenuation of dynamic pressure with borehole spacing